Progress Report for DOE-NEER Grant:

The Adjoint Method for the Optimization of Brachytherapy and Radiotherapy Patient Treatment Planning Procedures Using Monte Carlo Calculations

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June 2000

Introduction

The goal of this project is to investigate the use of the adjoint method, commonly used in the reactor physics community, for the optimization of radiation therapy patient treatment plans. Two different types of radiation therapy are being examined, brachytherapy and radiotherapy. Brachytherapy ("short distance" therapy) is the treatment of diseased tissue by physically placing radioactive sources within or very near the tissue. With radiotherapy, the source is usually located at a distance of about 1 meter from the patient and focussed on the treatment area.

Both radiation therapy procedures use similar solution methodologies and calculational tools that can be analyzed during the optimization process of either therapy procedure. The first year of the grant period was spent analyzing major components of the calculational procedure. The effect of adjoint source normalization, dose rate calculation using the flux-to-dose conversion factors, and the objective function definition for the optimization calculations were examined in the context of brachytherapy. The DANTSYS, discrete ordinates code system and the use of a simple geometric tissue region consisting of a sensitive structure embedded within a tumor region which is surrounded by normal tissue facilitated the brachtherapy calculations. GAMS, a general algebraic modeling system code system, was used for the optimization calculations. Adjoint monte carlo calculations using the MCNP code and the coupling of CT scan data to the MCNP geometric modeling routine were examined in the context of radiotherapy. Simple cylindrical shell problem with angular and spatial tallies simplified the understanding of the adjoint monte carlo method. Computed tomography (CT) data of the thorax region of a clinical patient was employed to develop the geometric coupling algorithm for MCNP.

This report summarizes the work that has taken place in these two areas over `the` course of first year of the grant.

Brachytherapy

In brachytherapy, sources implanted into tissue should be arranged so as to deliver significant dose to the target region (tumor) while sparing the normal tissue surrounding the target and any sensitive structures within the target. The purpose of this research is to use adjoint radiation transport techniques and an optimization algorithm to develop source distributions that are optimized in these regards. Source strength and location are the main factors that shape the dose distribution. The adjoint flux calculated by adjoint transport techniques can be interpreted as how important a given source position is to affecting the overall distribution of dose. By knowing the relative importance of all possible source locations, an optimization algorithm can be used to determine an optimal source distribution.

Two-dimensional adjoint calculations have been performed with the DANTSYS, neutral particle transport code package. The TWODANT (Two-Dimensional, Diffusion-Accelerated, Neutral-particle, Transport) code contained in the DANTSYS package computes the adjoint flux according to user-specified information about the geometry, material, photon group, and fluence-to-dose conversion factors.

Optimization of dose distributions has been performed with the constrained optimization solver (CONOPT2) in the GAMS (General Algebraic Modeling System) package. GAMS merges relational database theory and mathematical programming ideas for the needs of strategic modelers.

The geometry for the initial test problem simulates a typical optimization problem for the treatment of prostate cancer. As shown in Figure 1, a two-dimensional grid consists of Tumor (TU : 6 x 6 cm^2) which surrounds sensitive structure (SS : 2 x 2 cm^2) and is surround by normal tissue (NT : 10 x 10 cm^2). The square is divided by one hundred 1x1 coarse meshes, which are again divided by twentyfive 0.2 x 0.2 fine meshes. There are 100 (10 x 10) coarse meshes and 2500 (50 x 50) fine meshes in the geometry. Each coarse mesh voxel has 25 (5 x 5) fine meshes.
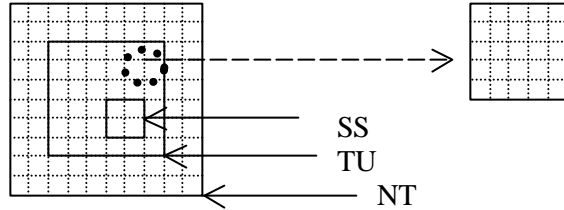
a) 100 coarse meshes   b) 25 fine meshes in each coarse mesh
Fig.1. Target geometry

Consistent with the materials, fluence-to-dose conversion factors, and other parameters specified for the problem, a 50 x 50 matrix of adjoint flux values is computed. Each adjoint flux represents how much each fine voxel would influence the course mesh if it had a source within a specified energy range. Sample results are shown in Figures 2a through 2d.
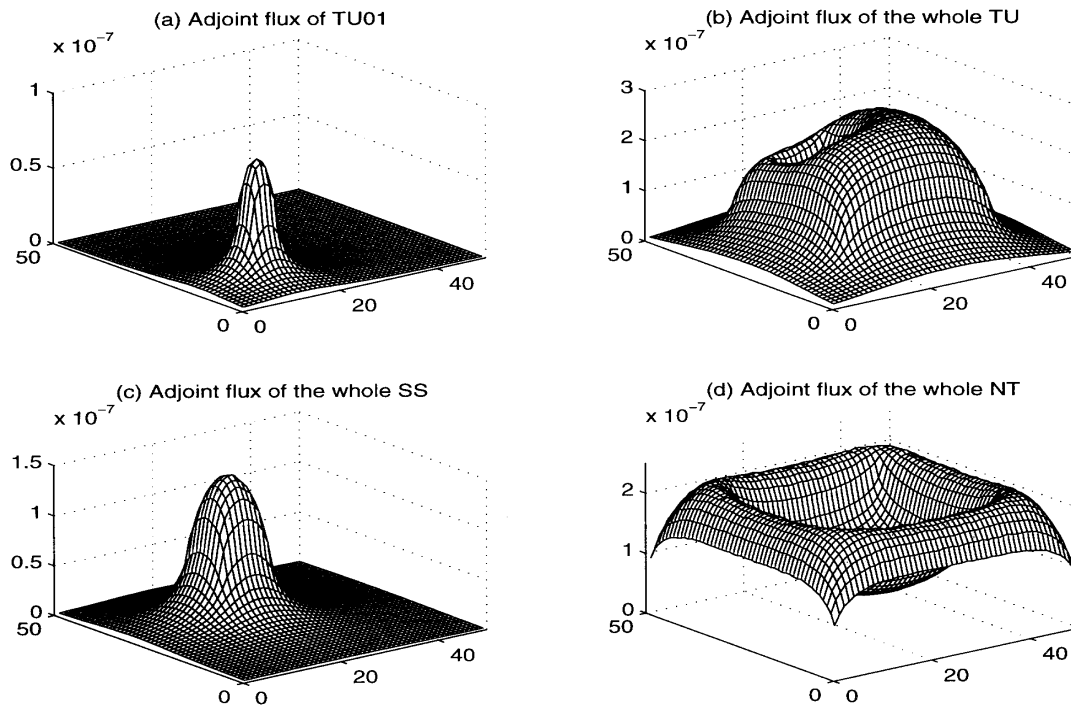

Fig. 2. Adjoint flux of the regions (a) the adjoint flux the first tumor region, (b) the adjoint flux of the whole tumor, (c) the adjoint flux of the whole sensitive structure, and (d) the adjoint flux of the whole normal tissue.

Once the adjoint flux matrix has been computed, dose calculations are performed with the equation:

$$Dose(V_d) = \frac{\sum\limits_{g=1}^{G}(\sum\limits_{s=1}^{N_s}(\sum\limits_{n=1}^{N_d}\Phi_n^+)_{s,g} * S_{s,g} * \Delta v_s)}{\sum\limits_{n=1}^{N_d} r_n \Delta v_n}$$

Dose(V_d)	: total dose in the detector region (course region)
V_d	: total detector volume

$$V_d = \sum_{n=1}^{N_d} \Delta v_n$$

$\Phi^+_{n,s,g}$	: adjoint flux of n voxel due to the g photon group source at s voxel
$S_{s,g}$	: g photon group source strength at s voxel
Δv_s	: volume of s voxel where a source places
Δv_n	: volume of n voxel which forms a detector (a coarse mesh)
ρ_n	: the density of n voxel. $\rho_n = 1$ because the example case is water
G	: the number of photon group. G = 3
N_s	: the number of source
N_d	: the number of voxels in a detector (a coarse mesh)

After the necessary dose calculations, optimization constraints are specified for the GAMS solver and a sample optimized source distribution is shown in Figure 3. The white pixels are the points where the source seeds should be planted. The black region in the middle, where the Cartesian coordinate $25 \leq x \leq 35$ and $15 \leq y \leq 25$, is the sensitive structure region and the black rim is the normal tissue region.
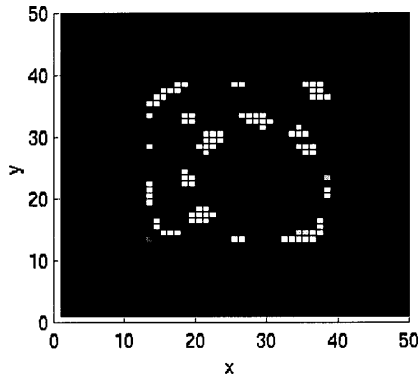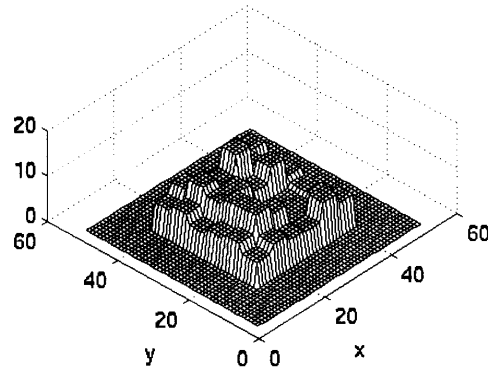

Figure 3

Figure 4

Using the GAMS input file with 10 mCi as the upper source strength bound, a typical resultant dose distribution is shown in Figure 4. This distribution shows no under dose in TU and no over dose in NT and SS. However, some TU regions adjacent to both the SS and NT receive a lower dose than other TU regions surrounded by other TU regions.

Radiotherapy

The Los Alamos code MCNP4B (Monte Carlo N-Particle version 4B) has been studied as part of an effort to develop a photon and electron-based dosimetry tool for radiation therapy treatment planning.

MCNP4B is a generalized Monte Carlo code capable of simulating coupled neutron-photon-electron problems using a three-dimensional, heterogeneous geometry system. To date, the scope of this effort has concentrated on two broad areas. The first has been manipulation of the generalized features of the code for forward and adjoint photon and electron dosimetry calculations. The second has been the study of computed tomography (CT) medical imaging techniques as a means of constructing a mathematical phantom for patient simulation and radiation therapy treatment planning. The following paragraphs briefly describe these areas of work.

Monte Carlo calculations with MCNP

The MCNP4B Monte Carlo code requires a user-defined input file specifying the necessary parameters for the problem geometry, radiation source, and scoring tallies for the simulation. Considerable effort has gone into investigating and understanding how to construct this input file so as to achieve credible results for different types of simulations.

MCNP4B is an attractive tool for dose calculation because it has forward and adjoint calculation capabilities. One of the inherent difficulties associated with Monte Carlo calculations is the amount of computer time required to generate statistically converged results of sufficient precision. Adjoint calculations, however, offer improved computational efficiency for situations where the source region is large relative to the detector region. For example, in radiotherapy applications where the dosimetric calculation region (e.g. tumor region) is small compared to the large number of different possible locations for the source, adjoint computations may be more efficient by orders of magnitude. Hence, considerable effort has gone into constructing input files for forward and adjoint calculations to understand how the two techniques must be implemented so that adjoint runs will yield the same results as forward runs. To date, these comparison calculations have been run only on test problems with simplified geometries; more complex cases with phantoms that simulate human anatomy will be run shortly.

CT Data

CT scanners are essential to radiation therapy because they provide diagnostic information about the location and size of tumors and dosimetric information about the region of interest such tissue composition and density. The basic yield of a CT scanner is an array of CT numbers -- one CT number for each volume element in the region of interest scanned by the machine. The CT numbers are related to tissue densities and tissue attenuation coefficients for diagnostic-energy x-rays. With the use of a calibration curve generated by scanning a phantom of known tissue types with known electronic densities, the array of CT numbers for a given scan can be converted to an array of tissue types and an array of tissue densities.
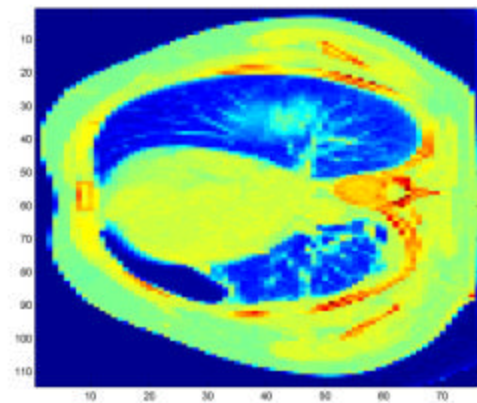

Figure 5

These arrays of material type and densities have been ported to MCNP4B input files for radiation transport and dose calculations. The figures shown are the preliminary results of such a process. Figure 5 is a single slice of a CT scan of a patient's thorax; Figure 6 is the same slice but in mesh format. Figure 7 depicts a depth dose calculation for an x-ray beam simulated as being incident normally on the anterior surface of the patient's thorax. The dose in tissue has been calculated in only 100 volume elements which represents only a small amount of the total area irradiated by the beam. Nevertheless, it is evident that dose values decrease with depth, as expected. Depth dose values were calculated with MCNP4B running under the UNIX operating system.
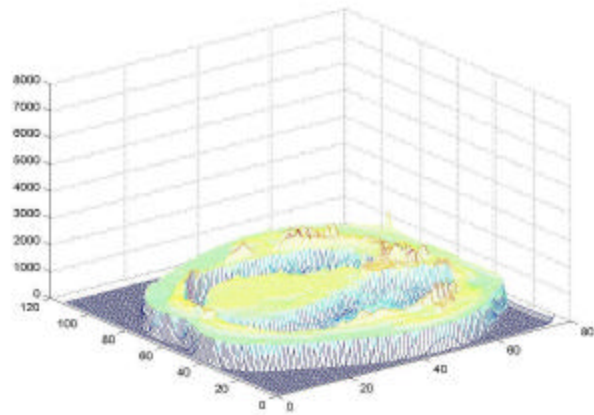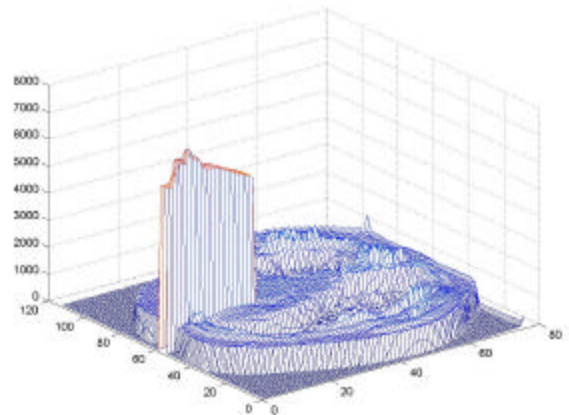
Figure 6

Figure 7